The Impact of Electric Mobility Scenarios in Large Urban Areas: the Rome case study

Carlo Liberto, Gaetano Valenti, Silvia Orchi, Maria Lelli, Marialisa Nigro and Marina Ferrara

Abstract — **In this work we evaluate the changes in energy demand and resulting climate-change and air pollutant emissions from the electrification of both the private vehicle fleet and the public transport fleet in the city of Rome (Italy). The study provides a Well To Wheel (WTW) analysis and considers two alternative hypotheses for the vehicles fleet renewal up to 2025.**

A data-driven approach is followed, where real traffic patterns from Floating Car Data are adopted as well as geo-referenced open-data published in GTFS format by Rome's public transport agency. Specific energy consumption models for electric vehicles have been calibrated, based on real driving cycles. Moreover, the economic benefit resulting from the reduction of externalities has been assessed.

Index Terms—**electric vehicles, battery electric buses, e-mobility, e-buses, floating car data, open data, pollutant emissions, energy consumption, computation of external costs**

I. INTRODUCTION

Reducing the primary energy consumption and the emissions of both Greenhouse gases (GHG) and toxic local air pollutants is nowadays one of the most serious issues affecting our societies.

An increase in the use of alternative fuels (biodiesel, gas, or electricity) and latest-generation vehicle engines represent a possible strategy in the transport sector to obtain significant emissions and consumptions savings. If combined with energy production from renewable sources, electric vehicles (EVs) can play a significant role for this outlook, and this is why, recently, a growing number of cities are introducing incentives for the promotion of this technology [1,2].

Electrification deals with both the private and the public transport sector: electric vehicles for private mobility were subject to a thorough investigation in the last years, especially for what concerns policies and environmental aspects.

In [3,4] authors discuss the performance of different electric vehicles promotional policies, such as subsidies and rebates, to evaluate customers preferences about alternative fuel vehicles. A Well-To-Wheel analysis of primary energy consumption and GHG emissions associated with EVs and conventional vehicles is presented in [5,6]. In [5], where the analysis is conducted considering the domestic electricity generation mix of different countries, results confirm that the GHG emissions attributed to EVs using electricity generated by fossil fuels are considerably higher than the emissions attributed to EVs using electricity generated by not fossil fuels. They also establish that EVs using electricity generated with coal or oil may be associated with higher GHG emissions than internal combustion engine vehicles (ICEVs). Instead, in [6] where the analysis is conducted in relation to the specific Hungarian power production mix, the results show that Well-To-Wheel emissions of EVs are equal to about half of those of ICEVs, but in terms of primary energy consumption, EVs do not perform significantly better because of the overall efficiency of the Hungarian power plants. Both the references underline the need to consider the specificities of the analysed country under both in terms of electricity generation mix as well as of the overall infrastructure system to evaluate correctly the environmental impacts of EVs versus ICEVs.

In [7,8,9] researchers have analysed the optimal design and location of EV charging stations. The goal of the optimization problem is to find the most suitable framework that ensures the minimum charging time, travel time and charging cost. Location of EV charging stations is a function of energy demand, both in terms of quantity as of its distribution in time and space. According to the European Environment Agency (EEA), the growth in electric vehicle use will result in an extra energy demand in the European Union, where Europe's total electricity consumption by electric vehicles will increase from approximately 4-5% in 2030 to 9.5% in 2050 [10]. Moving outside the European countries, [11] demonstrate that in the city of Los Angeles uncontrolled EV charging may push the overall system to a level beyond the grid's capacity, reaching in 2030, an energy load for EVs exceeding almost 17% of the entire generation capacity. Moreover, this increase in energy demand is not necessarily correlated to a growth in generation from renewable energy sources, because the time of day when most vehicles are recharged may influence which power plants are mostly used to cover the additional electric energy needs [12]. In such a context, a reliable evaluation of changes in energy demand results to be a fundamental step in order to deal with grid related problems occurring with the increase of the number of EVs.

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From the technology perspective, several studies investigated battery's type for improving autonomy and performance of electric vehicles. Energy management strategies, focused on Li-Ion batteries [13] and Lithium-batteries/Ultracapacitors [14], have been developed to evaluate the battery state of charge (SOC) in different conditions.

On the other hand, existing research on battery electric buses (BEBs) mainly deals on system design from the perspective of locations and size of battery charging stations [15,16,17]. Simultaneously, energy efficiency aspects are also addressed from the perspective of engine energy management strategies [18,19], battery management [20] and regenerative breaking technologies [21]. A recent contribution on BEBs [22] deals with the design and the evaluation of technological solutions for the electrification of public transport in urban areas, working at the level of single bus line and comparing technical, financial and environmental feasibility of several proposed architectures based on the most recent technologies.

This study evaluates the changes in energy demand and resulting climate-change and air pollutant emissions from the electrification of both the private vehicle fleet and the public transport fleet in the city of Rome (Italy). Similar to [12], a "what if" approach is adopted where two alternative scenarios are considered for the replacement of the internal combustion engine vehicles (ICEVs) with electric vehicles up to 2025. Moreover, economic benefit resulting from the reduction of related externalities is assessed.

With respect to other studies available in literature, our added value relies in considering both the private and the public transport fleet in the assessment, as well as in evaluating not only greenhouse gases, that are proportional to energy consumptions [23], but also air pollutants as CO, NOx, HC and PM, due to their impact on externality costs in urban environments.

The work provides a comprehensive analysis from a Well To Wheel (WTW) perspective, taking into account the entire production and distribution chain of the energy carrier.

The adopted methodology starts quantifying and characterizing the urban mobility, based on an extensive collections of geo-referenced data carried out by a sample of probe vehicles, as well as open-data about the planned service and the network structure of the public transport fleet of Rome.

Then, taking advantage of ECOTRIP (Emission and Consumption Calculation Software Based on Trip Data Measured by Vehicle On-Board Unit), a modelling tool developed by the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), geo-referenced estimates of the pollutant emissions, climate-change emissions and fuel consumptions are provided [24]. Recently we completely updated the tool in order to include the new European Emission Standards (Euro 5 and Euro 6), as well as hybrid, electric, light-commercial and heavy-duty vehicles, buses, mopeds and motorcycles. With regard to private EVs, a specific consumption function has been estimated from several datasets collected on both roads and roller bench tests. Instead, for BEBs an electric bus simulation tool has been adopted to obtain the related specific energy consumption model.

The outline of the remainder is as follows: in Section 2 we explain the proposed methodology for extracting traffic patterns through FCD and to reproduce the bus service through the open-data. Section 3 describes the estimation process of pollutant emissions and fuel consumptions, including the calibration of the specific consumption curves for EVs. In Section 4 we summarize the results for the case study of Rome in terms of energy demand and resulting climate-change and air pollutant emissions. Section 5 shows the external costs computation and, finally, Section 6 concludes the paper.

II. EVALUATION APPROACH

For a fair comparison of EV with ICEVs, we considered a Well To Wheel (WTW) rather than a Tank To Wheel (TTW) approach. In fact, the WTW embraced the whole energy life-cycle; starting from the extraction of energy from natural resources through transportation and distribution, and ending with transformation into kinetic energy to the wheels [25].

The WTW consumptions C^v_{WTW} for the fuel or energy vector v can be computed as:

$$C^v_{WTW} = C^v_{WTT} + C^v_{TTW} \tag{1}$$

with

$$C^v_{WTT} = C^v_{WTP} + C^v_{PTT} = C^v_{TTW}/\eta^v_{WTT} \tag{2}$$

where:

C^v_{TTW} is the TTW consumptions for the fuel or energy vector v;
C^v_{WTT} is the Well To Tank (WTT) consumptions for the fuel or energy vector v;
C^v_{PTT} is the Processing To Tank (PTT) consumptions for the fuel or energy vector v;
C^v_{WTP} is the Well To Processing (WTP) consumptions for the fuel or energy vector v;
η^v_{WTT} is the WTT energy efficiency for the fuel or energy vector v.

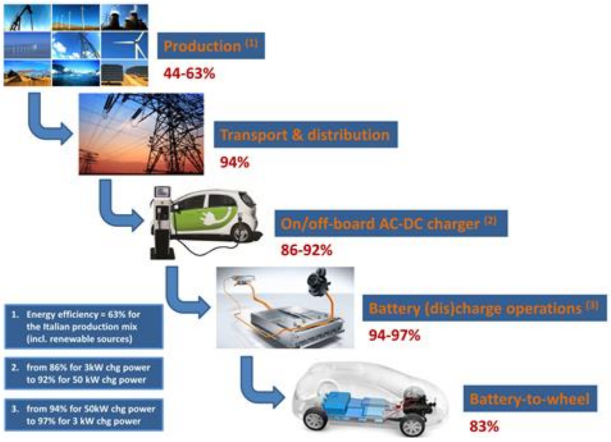

Fig. 1. Well-To-Wheel energy efficiency chain of electric vehicles [31, 32, 33]

Taking into account the production, refining and transportation of fuel, the current power supply distribution of vehicles in Rome, as well as the average kilometers travelled in urban and rural roads, the ICEVs WTT energy efficiency is around 85% [25], whereas the TTW energy efficiency is around 18% [26]. As for EVs, in the WTT efficiency factor we consider the energy efficiency (63%) of the Italian power production mix (including renewable sources) [27], as well as the average energy efficiency of electricity distribution and charging operations, respectively 94% and 90% [28, 29, 30].

The WTW energy efficiency of EVs is around 39% (Fig. 1). It should be noted that, in Italy, the renewable energy sources account for about 34% of electricity generation [31, 32, 33].

When moving to the computation of emissions, it is required the knowledge of specific emission factors linking Green House Gases, GHGs (CO_2 equivalent) and noxious pollutants with consumptions. As for the emission factors, we considered the upstream emissions associated with the production and distribution of the fuel or energy vector (Table I) and estimated from the National Inventory factors [34]. Thus, the whole Processing To Wheel (PTW) emissions for the fuel or energy vector v and pollutant i can be computed as:

$$E^{v,i}_{PTW} = E^{v,i}_{PTT} + E^{v,i}_{TTW} \qquad (3)$$

with

$$E^{v,i}_{PTT} = C^{v}_{PTT} \times f^{v,i}_{PTT} \qquad (4)$$

where:

$E^{v,i}_{PTT}$ is the PTT emissions for the fuel or energy vector v and pollutant i;

$E^{v,i}_{TTW}$ is the TTW emissions for the fuel or energy vector v and pollutant i;

$f^{v,i}_{PTT}$ is the PTT emission factors for the fuel or energy vector v and pollutant i.

TABLE I. PRODUCTION TO TANK EMISSION FACTORS

Emission Factors [g/kWh]	**Gasoline**	**Diesel**	**LPG**	**CNG**	**Electricity**
CO	0.00419	0.00419	0.00197	NA	0.0918
NMHC	0.049	0.013	0.006	0.036	0.0079
NOx	0.02206	0.02206	0.01037	NA	0.1948
PM	0.00086	0.00086	0.00041	NA	0.0043
CO_2 equivalents	34.75	34.75	16.33	15.02	323.63

Estimations of C^{v}_{TTW} in (1) and (2) as well as of $E^{v,i}_{TTW}$ in (3) are performed with ECOTRIP (Emission and Consumption Calculation Software Based on Trip Data Measured by Vehicle On-Board Unit), which requires specific information on traffic flow for private transport and on the bus service for the public transport. The proposed approach to retrieve such information is based on the adoption of extensive geo-referenced data collections to reconstruct the mobility patterns of private vehicles and to the adoption of open data usually published by public transport agencies.

Next subsections describe the data adopted and how they are processed in order to be inserted in ECOTRIP for the case of the city of Rome.

A. Reproducing traffic patterns by Floating Car Data

Nowadays, the use of massive FCD to extract traffic patterns and travel behaviors occurring in urban areas is extremely appealing [35, 36, 37]. It represents a reliable and cost-effective way to gather accurate traffic data over a wide-area road network and thus to improve many applications, such as location-based services, urban planning, and traffic management.

OctoTelematics (http://www.octotelematics.com) collects the FCD used in this study in order to provide added value services to car insurance companies and fleet operators.

In 2013, the FCD system operated by OctoTelematics was made up of about 2 million privately owned cars. Cars are equipped with an on-board unit (OBU) that stores GPS measurements (position, heading, speed, quality) and, periodically, transmits them to the Data Processing Center. The OBU consists of a GPS receiver, a GPRS transmitter, a 3-axis accelerometer sensor, a battery pack, a mass memory, processor and a RAM. The OBU stores GPS measurements every 2 kilometers travelled or, alternatively, every 30 seconds when the vehicle is running along a motorway or some main urban arterials.

In our analysis, we use two large datasets of FCD. The first includes about 150’000 cars tracked during the whole month of May 2013 in the metropolitan area of Rome (5’352 km² and about 4.3 million inhabitants). The second counts about 30’000 cars (owned by Rome residents) tracked during the whole year 2013.

We set up a processing procedure that corrects or removes possible measurement errors caused by failures in the tracking device. In fact, the accuracy of GPS data depends on the number of available satellites and strength of signal. Low accuracy can significantly affects the provided measurements resulting in positioning errors greater than 30 meters. In such cases, the whole sequence of traces may be discarded. OBUs also provides the information on the engine status: on, off or in motion, and, consequently, the origin-destination (OD) of each trip can be easily identified.

For each trip, we then determine the most likely route in the network by matching sequences of positioning data to a street digital map. We reconstruct the route between each OD pair by applying a map-matching algorithm [38, 39, 40, 41] that incorporates the street network topology, including prohibited maneuvers and turn restrictions information. The digital street network of Rome’s metropolitan area has a total length of about 25’000 kilometers, with 205’567 nodes, 249’844 links and 42’667 prohibited maneuvers.

The map-matching pipeline adopted can be summarized as follows: Step 1 – Select departure and arrival candidate links (within 30 meters from the GPS track); Step 2 – Calculate all possible routes from the candidate departure links to the arrival ones (A* search algorithm [42]); Step 3 – Choose among competing routes the one whose expected travel distance is closer to the FCD measured one.

Thus, from the first dataset we obtain the complete sequence of travels done in May 2013 by each individual car equipped with an OBU within the studied area. Overall, we derive approximately 14 million travels covering a total distance of about 117 millions of kilometers (Figure 2).

Once we have extracted the whole sequence of travels, including travel times and distances information, we apply the ECOTRIP software to compute fuel consumption and pollutant emissions for each OBU-equipped car taking into account the car category defined based on fuel type, engine size and Euro standard.

To derive the FCD penetration rate we follow the methodology already proposed in “Nigro et al.” [37]. In particular, we first set up a map-matching algorithm to reconstruct the most likely route between each origin-destination pair. We then compare the number of OBU-equipped cars traveling 38 sections of the metropolitan area of Rome with measurements from loop detectors placed in the same sections (Figure 2). By comparing FCD flows with the ones from loop detectors, we estimate a penetration rate of OBU-equipped cars of 6.43% (±0.12% at 95% CL) [24]. This value properly takes into account the different composition of the Roman vehicle fleet, as the flows provided by loop detectors refer to the complete fleet, including high duty vehicles, buses and mopeds, while the FCD flows are only related to passenger cars and light duty vehicles.

Moreover, we apply the Kolmogorov-Smirnov test to verify that the sample follows a normal distribution and the T-student test to verify the independence of the penetration rate from the road category.

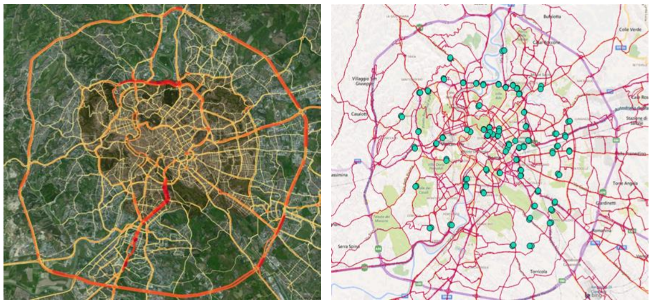

Fig. 2. Map-Matching algorithm results and traffic loop-detector map

The determination of the OBU-equipped car penetration rate allows us to estimate the energy consumption and pollutant emissions produced by the whole fleet of privately owned cars traveling studied area.

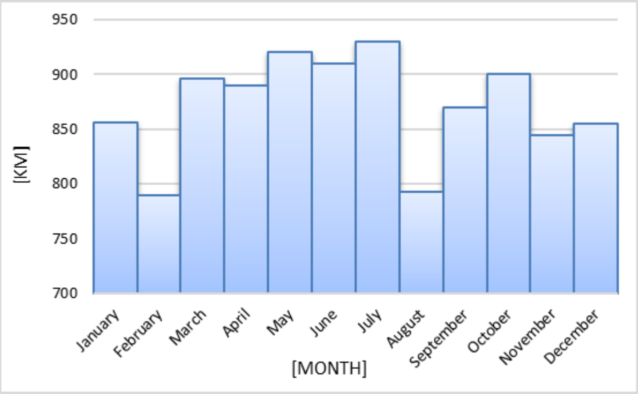

Fig. 3. Average monthly distance traveled per OBU-equipped car

We finally extend these monthly estimates to the whole year 2013 using the second dataset of FCD. To this end, we estimate the percentage (8.3%) of mileage driven by the fleet of OBU-equipped cars in May 2013 with respect to the annual mileages. Projecting from the FCD sample to the effective population, we obtain that the annual distance traveled by privately owned cars in the study area amounts to slightly more than $20x10^9$ kilometers. Statistics of the distance travelled by OBU-equipped cars are given in Figure 3.

B. Public transport open data and simulations

In the case of public transport, we make estimations of energy consumption and pollutant emissions by using ECOTRIP according to a set of parameters related to each pair of adjacent stops such as speed, traveling distance, passenger load factors and so on. Most of these parameters are derived from open-data published by transit agencies at a specific URL in the General Transit Feed Specification (GTFS) format. These data consist typically of basic operational data (e.g., number of stops, stop times, number of journeys), together with geographical information of the routes [43].

However, the total weight of buses can significantly vary in accordance with the number of the passenger on-board and this affects energy consumption and tail-pipe emissions. Since information on load factors is not available from the open data, a simulation model has been applied to obtain them. Specifically, we run a Public Transport (PT) simulation model taking into consideration the weekday Origin-Destination matrices representing the Rome’s PT travel demand during the peak and off-peak hours both in the morning and the evening. To extend simulation results to the remaining hours of the day we consider the daily profile of the traffic demand estimated from travel surveys by the Mobility Agency of Rome (Fig. 4).

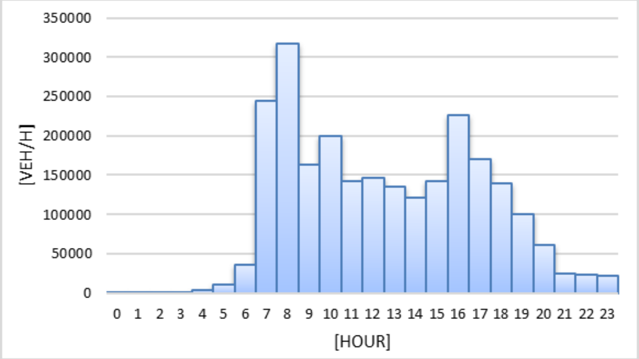

Fig. 4. Private vehicles daily demand (source: Mobility Agency of Rome)

Load factors for the nighttime have been obtained adopting a linear trend of the values between the 11:00 pm and the 4:00 am. For the summer weekdays, load factors previously computed have been reduced of -30% due to the lack of the school population and to the increased adoption of the car for that season. Finally, for the weekend days a reduction of -70% of the load factors has been hypothesized for both the winter and the summer season.

III. ESTIMATING POLLUTANT EMISSIONS AND FUEL CONSUMPTIONS (ECOTRIP)

ECOTRIP performs estimates of atmospheric pollutant emissions (Carbon Monoxide, Nitrogen Oxides, Non-Methane

Hydrocarbons and Particulate Matter), climate-change emissions (Carbon Dioxide) and fuel consumption produced by internal combustion engines. The evaluation procedures take into account the speed-dependent hot emission factors described in the EMEP/EEA emission inventory guidebook [44] which were obtained from several experimental measurements collected in different European countries. These factors vary according to the fuel supply, the European Emission Standards, the engine size for passenger cars and the weight for commercial vehicles and buses.

Recently, ECOTRIP has been updated in order to include the new European Emission Standards (Euro 5 and Euro 6), as well as hybrid, electric, light-commercial and heavy-duty vehicles, buses, mopeds and motorcycles.

For private vehicles, estimates are done for each segment located between two consecutive GPS traces of a journey combining the vehicle features together with the geographical information of the routes.

Instead, in the case of public transport, estimates are done for each segment located between two consecutive stops of a journey according to the bus type in respect of its size (Mini, Midi, Standard and Articulated) and propulsion system. Moreover, it is possible to assess the effect of road slopes and vehicle load factors.

In addition to hot running emissions, ECOTRIP accounts for the “cold start” emissions, occurring when engines and catalysts are not (fully) warmed up and operate in a non-optimal condition. The estimation of the extra cold emissions refers to the methodology developed by INRETS (*Institut national de recherche sur les transports et leur sécurité*), which is based on several experimental tests performed in different European laboratories, as described in the ARTEMIS European Project [45].

However, as the consumption of electric vehicles is not considered in [44], we have built specific consumption functions for both private EVs and BEBs, as described in the following subsections.

A. Estimation of the private EVs consumption function

The experimental function associates consumptions with the average speed of the vehicle and it was obtained combining data from on-road measurements and from roller bench tests. In both cases, a Nissan Leaf car has been used. It is a vehicle with 100% electric drive train and a regenerative braking drive mode, not producing any kind of exhaust emission. The lithium ion battery has an autonomy of 175 kilometres and can be recharged through a socket located in front of the vehicle.

The data collected in the on-road tests cover a period of about one year, for a total amount of 3’600 kilometres travelled on both urban and interurban roads. The roller bench tests follow the predefined driving cycles ECE15-NEDC (New European Driving Cycles) [46] with a time duration of 1’180 seconds (20 minutes). The vehicle is fixed on the bench, the driving wheels are placed on the rollers, while the others are locked. Each test consists of following the standardized driving cycles, while data on the engine state, driving conditions and battery state are recorded by an on-board system.

The experimental function obtained for the Nissan Leaf and adopted in ECOTRIP for the consumptions computation is reported in Figure 5.

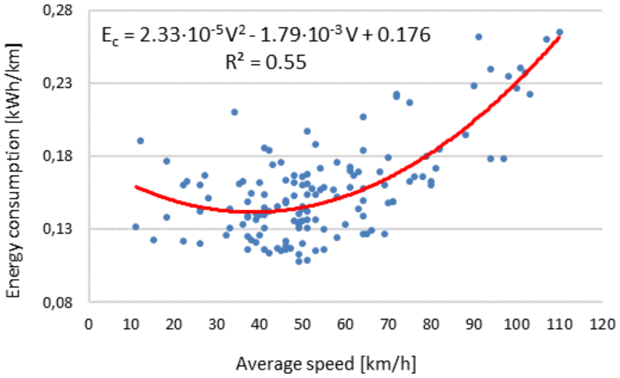

Fig. 5. Experimental consumption function for electric vehicles

B. Estimation of the BEBs consumption function

Specific consumption functions have been calibrated, by simulating electric buses on real driving cycles derived by a number of buses operating in three Italian cities (Ravenna, Turin and Bologna). The simulation process considers several load factors (0, 50 and 100% passenger load factor), road slopes (-4, -2, 0, +2, +4%). and four different types of bus, namely Mini, Midi, Full and Articulated. Thus, for each vehicle type, passenger load factor and road slope, energy consumption variation with vehicle mean service speed was approximated with a best fitting 2-parameters exponential function cruise. It was so possible to obtain 2’880 specific speed-consumption curves to be used within ECOTRIP.

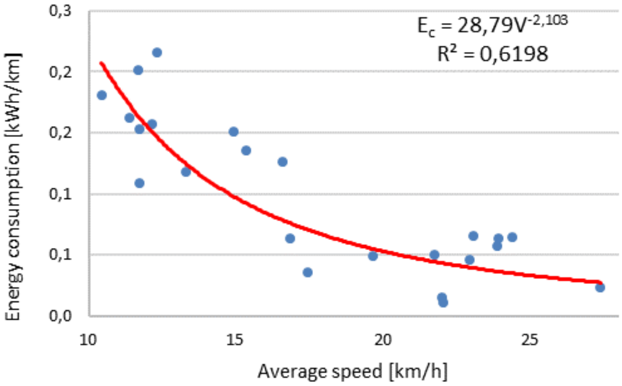

Fig. 6. Consumption factor for Standard Electric Bus obtained with 50% of load factor and -4% of road slope

A deeper detail about the consumption functions estimation can be found in [47], while here, only a Figure has been reported (Fig. 6) as an example of modelling result in terms of energy consumption and of their dependence on the cruise speed.

IV. CASE STUDY

In the present analysis, we take into consideration the current situation and two prospective scenarios up to 2025, according to the Electric System Research Programme (RdS) supported by the Italian Ministry of Economic Development (http://www.enea.it/it/Ricerca_sviluppo/lenergia/ricerca-di-sistema-elettrico).

In case of private vehicles, the current scenario (Scenario_0) supposes the OBU-equipped cars fleet composition to be the same as that of the privately-owned cars registered to Rome residents in 2013 (ACI statistics, http://www.aci.it), see also Figure 7.

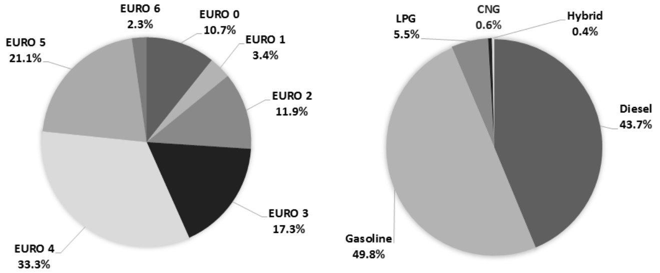

Fig. 7. Current car fleet composition based on emission standards and fuel type in Rome

Instead, current bus fleet composition regarding fuel type and emission standards is showed in Fig. 8.

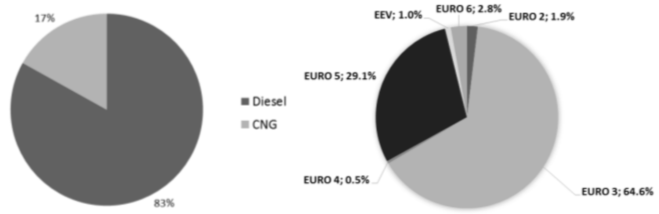

Fig. 8. Fleet composition based on fuel type and European Emission standards

At present in Rome, transit agencies operate a fleet of 2’440 buses of which 400 are CNG fueled buses. The bus network has 8’719 stops and 10’679 links (between stops) with an extension of about 5’000 km. The bus service on a weekday includes 324 routes and 34’417 journeys with a total distance travelled of about 329’000 km. Distances travelled from/to the depots amount to about 5% of the daily kilometres. Overall, we estimate that the annual distance travelled by Rome bus fleet amounts to about 132 million kilometres.

As for the two prospective scenarios, we assume two different projections for the market penetration of electric cars.

In the first prospective scenario (Scenario_1) we suppose a negligible market penetration of electric cars and a car fleet renewal rate reflecting the latest trends and forecast for the automotive sector. In particular, we assume an average annual renewal rate of 5% largely based on ICE cars meeting the EURO 6 standard for exhaust emissions of NOx and other pollutants. Besides, we consider a slight growth of the privately-owned car fleet and a higher penetration of both hybrid electric cars (2%) and CNG-powered cars (1.2%) in 2025. About the bus fleet, we consider a fleet renewal percentage of 30% largely based on EURO 6 buses, replacing the oldest diesel vehicles (EURO 2 and EURO 3).

In the second prospective scenario (Scenario_2), we assume the car fleet renewal and growth rate to be exactly the same as in the first prospective scenario, but with a consistent penetration rate of electric cars (10%) in place of the ICE cars under EURO 6 homologation standards. For the bus fleet, the renewal percentage is the same of the first scenario but 30% of the oldest diesel buses (EURO 2 and EURO 3) are instead substituted by BEBs. The percentage of CNG bus remains unchanged in all the scenarios.

It is worth noticing that we assume travel patterns, times and distances, extracted by combining FCD and loop detectors measurements, as well as bus lines and service schedule, remain unchanged up to 2025.

A. *Results*

This section presents the main findings obtained for different electrification scenarios of both private and public transport of Rome. Results for the private and public sectors have been reported separately as their overall impact on fuel consumption and pollutant emissions is, for obvious reasons, very different.

As for the current scenario, TTW estimates related to the private vehicle fleet indicates that the annual consumption of gasoline and diesel amounts to about 665’000 tons and 520’000 tons respectively. These estimates are broadly coherent with the current annual sales of gasoline and diesel in the studied area, with an observed difference of about 4%. According to the WTW life cycle, analysis related to the current scenario, the annual primary energy consumption amounts to about $1.5 \cdot 10^6$ toe (tons of oil equivalent) including contribution from cars running on LPG and CNG (Fig.9).

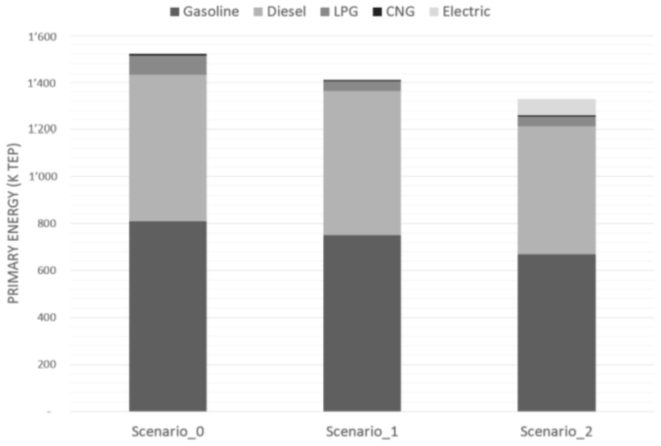

Fig. 9. Annual primary energy consumption estimates due to private vehicles renewal

Moving to the two prospective scenarios, the WTW life cycle analysis shows significant reductions compared to the current scenario in terms of primary energy consumption and CO_2-equivalent GHG emissions (cf. also Figure 9).

Specifically, the prospective Scenario_2 leads to higher primary energy savings compared to both the current Scenario_0 (12.7%) and the prospective Scenario_1 (5.8%). However, the higher penetration of electric cars of Scenario_2 involves a higher electric energy consumption of about 434 GWh per year.

Slightly better results are obtained in terms of CO2-equivalent GHG emissions reductions. Compared to the current scenario and the prospective Scenario_1, a 10% penetration rate of electric cars can contribute to a CO2-

equivalent GHG emission reduction of 13.1% and 7.8%, respectively.

The prospective Scenario_2 also provides noticeable reductions in the total noxious air pollutant emissions both at local and global level. Compared to the current scenario, the estimated emission reductions for CO, NOx, HC and PM range from 50% to 70%. These reductions are predominantly due to the current high number of cars with old emission standards. In fact, much lower reductions (from 6% to 8%) result from comparing the two prospective scenarios.

By way of example, in the Figure 10, we show the weekday profile of PM emissions estimated in the three scenarios.

Scenario_2 could actually achieve higher reductions compared to Scenario_1, especially for NOx and PM emissions. In fact, recent evidences [48,49,50] indicate that current emissions from diesel cars meeting EURO 5 and EURO 6 standards measured on laboratory tests do not reflect the emissions in normal driving conditions (Commission Regulation (EU) 2016/646 of 20 April 2016).

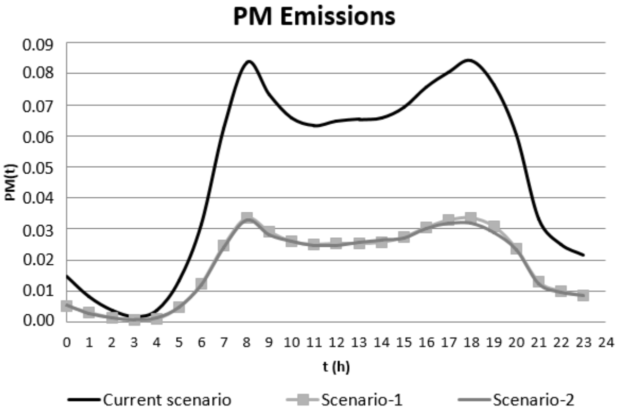

Fig. 10. Weekday profile of Particulate Matter emissions due to private vehicles

As for the public transport fleet, our estimates indicate for the current scenario an annual consumption of diesel and CNG of about 41 million litres (34’500 tons) and 14’390’244 Nm3 (normal cubic meter) respectively.

For the two prospective scenarios, results show that Scenario_2 implies a 22% reduction of energy consumption. This reduction is much higher than the one estimated in Scenario_1, amounting to about 3%. In Scenario_2 the estimated annual electric energy consumption is about 34 GWh.

Table II shows the details of these reductions differentiated by fuel type.

The changes in pollutant and greenhouse gases emissions between scenarios are reported in Fig. 11. Compared to the current scenario, considerable pollutants emissions reductions can be obtained with the renewal of the fleet by EURO6 buses and even more with the BEBs: -36% for CO, -33% for HC, -37% for NOx and -50% for PM. Annual emissions of greenhouse gases (CO2) are reduced of 30%. The reductions in terms of PM are especially relevant, since this pollutant has dangerous effects on human health. Moving from Scenario_1 to Scenario_2 an additional reduction of 12% can be obtained.

For Scenario_2, the WTW life cycle analysis shows significant reductions compared to the current scenario in terms of primary energy consumption (-17%) and CO2-equivalent emissions (-23%).

TABLE II. CONSUMPTIONS REDUCTIONS OF FUEL AND ENERGY BY FUEL SUPPLY (PUBLIC TRANSPORT)

Energy Consumptions [GWh per year]			
Fuel supply	***Scenario_0-Scenario 1***	***Scenario_0-Scenario_2***	***Scenario_2-Scenario_1***
Diesel	-20	-161	-141
Electric	-	+34	+34
TOTAL	-20	-127	-107
Fuel Consumptions [tons per year]			
Fuel supply	***Scenario_0-Scenario 1***	***Scenario_0-Scenario_2***	***Scenario_2-Scenario_1***
Diesel	-1’645	-13’540	-11’895
Electric	-	+2’855	+2’855
TOTAL	-1’645	-10’685	-9’040

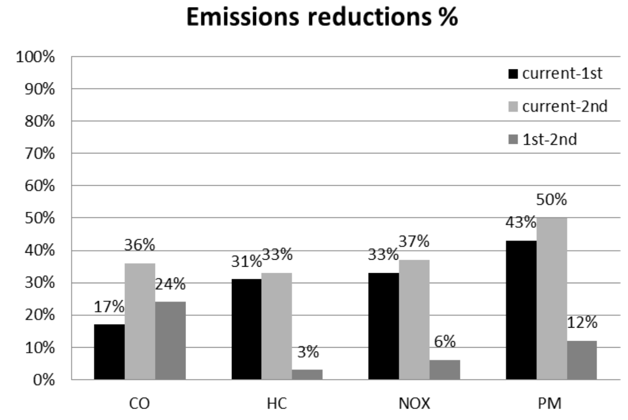

Fig. 11. Reductions of pollutant emissions for different scenarios due to public transport renewal

TABLE III. POLLUTANT EMISSIONS REDUCTIONS (PUBLIC TRANSPORT)

Pollutant	***Scenario_0-Scenario 1***	***Scenario_0-Scenario_2***	***Scenario_2-Scenario_1***
CO	-17%	-36%	-24%
HC	-31%	-33%	-3%
NOx	-33%	-37%	-6%
PM	-43%	-50%	-12%

It is important to note that the estimated reductions depend on the current carbon-intensity of the Italian power grid mix; as a result, the expected growing share of renewables in the electricity production could lead to higher reduction rates of primary energy consumption and GHG emissions.

V. ESTIMATE OF THE REDUCTION OF EXTERNAL COSTS

Road traffic generates a series of externalities that impact on the community, without being contemplated in the cost sustained by transport users. To remedy this market flaw it is necessary to apply a methodology and quantify the damage generated by transport externalities.

Our methodology is based on the latest handbook published by the European Commission for evaluating external cost of transport [51]. We evaluate externality damages from the PTT phase to the TTW phase taking into consideration noise, air pollutants and greenhouse gases emissions.

TABLE IV. SPECIFIC COST PER KILOMETER

	Harmful emission	***Noise***	***Total***
Scenario_0	***€/km***		
Gasoline	3.71	1.78	5.5
Diesel	4.33	1.65	6.0
LPG	2.50	0.20	2.7
CNG	2.47	0.03	2.5
Hybrid	0.24	0.01	0.3
Total	3.90	1.62	5.52
Scenario_1	***€/km***		
Gasoline	2.77	1.75	4.52
Diesel	3.17	1.58	4.75
LPG	2.04	0.20	2.24
CNG	3.19	0.06	3.25
Hybrid	1.29	0.07	1.36
Total	2.88	1.54	4.41
Scenario_2	***€/km***		
Gasoline	2.49	1.54	4.03
Diesel	2.90	1.60	4.50
LPG	2.04	1.54	3.58
CNG	3.21	2.05	5.26
Hybrid	1.21	1.34	2.54
Electric	0.63	1.00	1.62
Total	2.42	1.51	3.93

As for the noise emission cost related to each scenario, we first used the acoustic emission levels, expressed in decibel, for each technologies [52] and then we estimated the reduction of the specific noise costs according to the different ranges of noise emissions [53]. Specifically the CNG vehicles produce the same damages than diesel ones, while hybrid and electric vehicles cut the damage of 13% and 40% respectively. Moreover, we considered the different noise costs on the basis of the time of the day.

The estimated total annual mileage in the urban area of Rome amounts to 20.8 billion km, whereas public transport accounts for less than 1% of the total (132 million km). Private transport causes negative externalities for over one billion euro per year, amounting to 96% of the total, of which 68% is from harmful emissions and the remaining 32% from noise. Public transport would generate 40.5 million of euro of damages, of which 78% is produced by harmful emissions and 22% by noise emissions.

Table IV shows the specific costs per kilometer for each scenario, obtained by combining the external costs and the distance traveled using the different fuels. Compared to Scenario_0, Scenario_1 reduces the external costs by 20% from 5.52 €/km to 4.41 €/km, in the Scenario_2 the final cost goes down of about 29%, to 3.93 €/km.

VI. CONCLUSIONS

This study evaluates the changes in energy demand and pollutant emissions due to the introduction of electric vehicles and battery electric buses at the level of wide urban area. Following a well-to-wheel approach, we compare two alternative scenarios for vehicles renewal up to 2025. Finally, an assessment of the economic benefit resulting from the reduction of externalities in the prospective scenarios is reported.

The methodology is based on the adoption of real traffic estimates from Floating Car Data, as well as of open data and simulated data of the studied bus service. The ECOTRIP model is then used to perform estimates of atmospheric pollutant emissions, climate-change emissions and fuel consumption. To deal with EVs, *ad hoc* consumption models have been calibrated and implemented in ECOTRIP.

Results obtained in the real case study of the city of Rome (Italy) confirm the importance of EVs for achieving sustainable mobility goals. In fact, a partial electrification of the private vehicles fleet (10% of EVs to 2025) and the public transport fleet (30% of BEBs to 2025) can induce a significant reduction in the primary energy consumption, with respect to both the present situation (12.9%) and the other hypothesised scenario (6.2%). We estimate that the partial electrification would require an amount of energy equal to about 460 GWh, 2.9% of the total electricity used in the province of Rome in 2015. The study also reveals a significant decrease in CO2 emissions, as well as a remarkable reduction in noxious emissions that are harmful to the human health, especially in urban areas.

The external costs, calculated for harmful emissions and noise, account for over one billion damage per year in the city of Rome. Although private mobility has the biggest part, generating 96% of the total value of the damage, there is no doubt that the driving force for change should come from local public transport which is one of the most important alternative to private mobility in urban areas. However, the increasing number of vehicles with low environmental impact in the market, could contain these damages of a percentages ranging from 20% to 26%.

Future developments of this research will be oriented in: (i) adopting the recent approved “World-wide harmonized Light vehicles Test Cycle” (WLTC) for deriving energy consumption function, since WLTC has been founded to better represent the real-world driving conditions with respect to the New European Driving Cycle (NEDC) here adopted [54]; (ii) test the FCD representativeness in terms of vehicle fleet; (iii) finally, investigating possible future mobility scenarios for EVs with the aim of relocating the energy demand in order to avoid the exceeding of the grid capacity.

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